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Heat Stress & Damage In Trees

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Summer provides many hot dry weeks for people and trees. Figure 1 shows the historic number of days with temperatures above 90°F for the State of Georgia. Much of tree growth is impacted by water availability and heat load issues. Many old, young, and soil-limited trees are susceptible to damage. The combination of drought and harsh site conditions around parking lots, along streets, on open squares, and with surrounding pavement lead to a number of tree problems. An old folk term "heat stroke" can be used with trees where heat loads are extreme and have led to tree growth and survival problems.

Temperature

Trees find optimum growing conditions across a range of temperatures from 70°F to 85°F. Hot temperatures can injure and kill living tree tissues. A thermal death threshold is reached at approximately 115°F. The thermal death threshold varies depending upon duration of hot temperatures, absolute highest temperature reached, tissue age, thermal mass, water content of tissue, and ability of a tree to make adjustments with temperature changes.

Tree temperature usually runs just at or slightly above air temperature in sunlight. Trees dissipate heat by radiating long-wave radiation, convection of heat into surrounding air, and transpiration (water loss from leaves). Transpiration is a major mechanism for dissipation of tree heat loads. Without transpirational cooling, more ineffective means dissipate heat, like radiation to surroundings and wind cooling.

Water Control

Trees can dissipate tremendous heat loads if allowed to function normally and with adequate soil moisture. Unfortunately, hot temperatures greatly increase water vapor pressure deficient (dryness of the air) which causes leaf stomates to close because of rapid water loss, and so limits photosynthesis and transpirational cooling. When transpiration is limited by hot temperatures, and a tree is surrounded by non-evaporative surfaces (hard surfaces), leaf temperatures may approach the thermal death threshold.

Normal range of water contents over which tree growth occurs is -0.2 to -12 bars. Drought damage occurs in a leaf as -15 to -20 bars is approached. The gradient between the inside of a leaf at 100% relative humidity (0 bars) and the surrounding atmosphere can be great. Figure 2. For example, fog is close to 100% relative humidity while Summer rain downpours range from 90% to 98% relative humidity. Trees loose water during rain storms because at 98% relative humidity, the air is 100 times drier than the inside of a leaf. Trees are always losing water.

Keeping Up

Associated with rapid water loss and temperature increases in leaves, is a delay or time lag in water absorption by roots. Leaves can lose water much faster than roots can absorb water. The difference between water loss from a tree top and water gain through root absorption, can generate many problems. Figure 3 provides a generalized view of tree water movement with leaf transpiration and root absorption processes. Note that a noon-time slow-down in transpiration is caused in-part by water shortages in leaves, which causes stomates to temporarily close.

Water shortages developed in the day are corrected as completely as soil water content allows by root water uptake at night. The force or energy for this nighttime water absorption (when stomates are closed) is through reduction of tension (negative pressure) in water columns which remains from the previous day. This tension force pulls water into a tree. Night uptake by roots can amount to 20-40% of total tree water needs.

Hot Water

Heat injury is difficult to separate from water problems, because water and temperature in trees are closely bound together in biological and physical processes. Water shortages and heat buildup are especially critical in leaves, and secondarily, in cambial and phloem area of twigs and branches. On average sites, a difference of 22°F and 60% relative humidity can occur over a single day. As daytime temperatures increase, relative humidity plummets. Figure 4. Increasing temperatures greatly increases vapor pressure deficit between leaves and atmosphere, which drives mass flow of water through tree tissues and out of leaves. Figure 5.

In tree leaves, wilting is the first major symptom of water loss excesses and heat loading. Leaves under heavy heat loads may progress through senescence (if time is available), brown-out and finally abscise. Leaves quickly killed by heat are usually held on a tree by tough xylem tissue and lack of abscission zone preparation. Rewatering after heat damage and drought may initiate quick leaf abscission.

Hot Air

Long distance movement of sensible heat (energy) across landscapes is called advected heat. Advected heat is generated when hard dense surfaces heat the air above them. This advected heat is carried on the wind, heating and drying neighboring tree tissues as it passes. Advected heat from surrounding hardscapes can heat and dry trees, powering excessive water evaporation from trees and landscapes to dissipate heat generated somewhere else. Wind also decreases the protective boundary layer resistance to water movement around tree tissues and can lead to quick dehydration. Structures and topographic features can modify or block advected heat flows across a site.

Double Trouble

Daytime energy exchanges and associated temperature provide for a large heat load, but night temperatures are also critical for many tree growth mechanisms, especially new leaves and reproductive structures. Night temperatures are critical for respiration rates in the whole tree and soil environment. The warmer the temperature, the geometrically faster respiration precedes.

As a general rule, each temperature step, beginning at 40°F and continuing through 58°F, 76°F, 94°F, 112°F, and 130°F, allow physical doubling of respiration and water loss. Figure 6. Photosynthetic rates generally double up to 94°F, and then rapidly fall-off. Respiration in all living tree tissues continues to rapidly climb until thermal death levels are reached. Heat stroke in trees is a series of metabolic dysfunctions and physical constraints which pile-up inside trees and become impossible to adjust, avoid, or correct. Figure 7.

Additional Stress

Since processing nitrogen is physiologically demanding, moderate concentrations of nitrogen fertilizers can lead to tissue and system damage under large heat loads. The internal processing of nitrogen fertilizer inputs require stored food (CHO) in roots be used. Under large heat loads and water loss levels, no food can be produced in a tree, transport systems are only marginally functional, and respiration is accelerating. Under these conditions, nitrogen applications should be withheld until heat and water stress levels are normalized.. Excessive heat loads and supplemental nitrogen lead to excessive root food use. Fertilizer salt contents or activity in a soil can also be damaging to a tree when soil moisture is limiting.

Heat stress problems make trees more susceptible to pests and other environmental problems. A number of pathogenic fungi are more effective in attacking trees under water or heat stress. Physical heat injury includes scorching of leaves and twigs, sunburn on branches and stems, leaf senescence and abscission, acute leaf death, and shoot and root growth inhibition. These damage symptoms can allow pest entrance into a tree. Loss of defensive capabilities and low food supplies allow some otherwise uncommon or minor pests to effectively attack trees.

Hot Soil

The soil surface can be both a heat reflecting and absorbing layer. In full sunlight, dry dense soils can reach 150^{o}F. This heat can be radiated and reflected into a landscape and onto trees causing tremendous heat loading. Excessive heat loading causes large amounts of water to be transpired, initiates major metabolic problems, and can generate heat lesions just above the ground / tree contact juncture (root collar — stem base area). Heat lesions are usually first seen on the south / southwest side of stems.

The absolute temperature reached (above optimum functional level) partially determines heat stress recovery time needed. Figure 8. The duration of hot temperatures can not exceed a tree's ability to adjust, avoid, or repair problems, or death results. Less absolute amounts of sensible heat are needed to damage trees as the duration of hot temperature periods lengthen. In other words, the more dysfunctional and disrupted growth functions become, the easier it is to develop further stress problems.

Melting Membranes

Living tree cell membranes are made of a double layer of lipids (fats/oils) containing the living portions of a cell. As temperature increases, membranes become more liquid (similar to heating butter and watching it melt). As temperatures increase, cells use two strategies to maintain life — one is to increase the saturated fat proportion in membranes, and the second is to increase structural proteins holding membranes together. As temperatures continue to climb, enzymes and structural proteins are inactivated or denatured. Respiration pathways dead-end, producing toxic materials difficult to transport away, destroy, compartmentalize, or excrete. Tree cell death is the end result.

Tolerance

The differences among trees to tolerating heat loads revolve around enzyme effectiveness and membrane health. The better enzymes and membranes can be protected from heat effects, the more effective a tree will be in dealing with large heat loads. Protection or deactivation of enzyme systems in trees are influenced by pH, solute levels in cells, other protein concentrations, and active protection mechanisms. The ability of a tree to continue functioning under significant heat loads demonstrates tolerance. Tolerance mechanisms are primarily genetically controlled, although each individual usually has a range of responses to heat stress based upon current and past stress levels.

Heat Impacts

There are many internal changes within a living tree as heat loading increases. At first, photosynthesis (Ps) decreases and respiration (Rs) increases. Maintenance requirements of chlorophyll molecules greatly increase. As heat loading continues, net photosynthesis closes down altogether. The turn-over point between net photosynthesis and accelerating respiration is around 95oF. Although no net photosynthesis is occurring, chlorophyll molecules in sunlight continue to activate (fire electrons) and generate cell and chloroplast damaging by-products.

Going ...

As heat loads increase, transpiration greatly increases simply from physical water evaporation. Stomates are closed. With closed stomates no carbon dioxide (CO2) can be captured and no food (CHO) can be made. Closed stomates do not prevent evaporation of water from tissues, just transpiration through stomates. As transpiration is almost stopped, heat dissipation is prevented and internal tissue temperatures increase, accelerating respiration. As tissue temperature increases, more evaporation through the periderm and leaf / bud surfaces occur. Without transpiration generated forces, hydration, material transport, and absorption problems are magnified.

Heat increases continue to initiate cell membrane leakage and tissue dehydration, starting with the most tender and succulent tissues, like new leaves and shoots. Within the meristems (growing points or areas), cell division and expansion are inhibited, and growth regulation is disrupted. Trees rapidly use food reserves, while food transport and processing become more inefficient. In leaves, photorespiration accelerates making any photosynthesis more inefficient. Lack of effective transport mechanisms and control systems interfere with shipment and use of food reserves.

...Going....

As damaging heat load duration or temperatures continue to increase, tree cells start to self destruct. Within living cells, highly reactive and toxic materials are generated. Cell membranes begin to fail causing intermixing of materials within a cell and just outside in cell wall spaces. With continued heat load, the respiration system begins to fall apart. Growing spot deficiencies of essential elements, coupled with empty or overflowing pools of sequential metabolites occur. Cells can not work fast enough to keep everything from failing.

Gone!

Finally, excessive heat load leads to a complete loss of membrane integrity. The boundary between symplast and apoplast cannot be maintained and is lost. Proteins begin to functionally collapse and breakdown. The final result is dead tissue patches. These islands (lesions) of cell death expand, leading to massive damage which surrounding cells can not hinder or compartmentalize fast enough. Tree death is the final result.

Therapeutics

There are a number of appropriate responses to increasing heat load, and associated tree stress and strain. Many treatments are simply tree-literate common sense. Other treatments can be used to minimize damage and hasten recover.

Water!!!!!

Clearly the best treatment for increasing heat load is watering, sprinkling, and misting tree tissues to improve water availability, reduce tissue temperature, and lessen water vapor pressure deficit around tree tissues. Along with increased water supplies, come increased drainage demands for assuring proper soil aeration. Do not compound heat load problems with generation of suffocating anaerobic soil conditions.

Disrupt Heat Load Process!

To reduce heat loads on trees, partial shading can be used to reduce total incoming radiation but not filter-out photosynthetically active radiation. Shading as little as 10-20% of the full sunlight (i.e. allowing 80% to 90% of full sun to impact a tree and site) can significantly reduce heat load and increase efficiency of food and water use.

Reflection of sunlight and muting of radiative heat using site colorants (light colors and white) and surface treatments (low density, evaporative surfaces) on hardscapes around landscapes can reduce heat loads. Block or channel advected heat away from trees and soils with low density (i.e. wood) walls and fences, and soil berms. Hardscape watering is a water intensive / expensive procedure to quickly alter heat loads. Pervious evaporative pavements and low density non-heat absorbing surfaces can help minimize or dissipate heat loads.

Mulch In Moderation!

A key landscape treatment is the use of mulch which protects soil surfaces from direct sunlight impact and minimize indirect heat load impact. The best mulches are low-density, coarse textured, natural organic materials. Mulch purpose and function is to minimize soil evaporative water loss while not disrupting soil gas exchange processes (i.e. oxygen (O2) into soil and carbon-dioxide (CO2) out of soil).

Many blanket, film, and synthetic mat mulches tend to increase heat loading on a site and damage soil and trees. Size-sorted wood chips, tree bark, pine straw, and course leaf mulch work well if they are applied in thin layers, maintained, and do not mat or settle down into a water and gas impervious layer. Thin mulch layers are best — reapplied often.

Save Additions For Later!

During extreme heat load periods, some tree and site treatments can be damaging and should be delayed. Any and all forms of nitrogen fertilizer applications in or around a tree should cease. Resume minimal and then normal nitrogen enrichment only after full leaf expansion in the next growing season, or after soil and climate have returned to ecological normal growing conditions.

Prevent or minimize any soil active / osmotically active soil additives which might increase salt index or utilize water for dilution or activation. Be cautious of pesticide applications, carefully noting tree and soil activity of active ingredients, carriers, wetting agents, and surface adherence compounds. A number of pesticides require an active healthy tree and site for best response. Pesticide performance under hot temperatures, and with damaged trees, may be compromised generating unexpected results.

No Other Stresses!

For trees under significant heat loads, green-wood pruning should be minimized or delayed. Heat loads disrupt effective wound response, xylem transpiration pathways, and food reserve availability. Pruning should be avoided under high temperatures. Pruning will not improve tree heat stress levels, and can greatly deepen other problems.

One component once used in old landscapes (and seemingly forgotten in modern landscapes) was shade structures and wind screens. Utilization of well-designed and constructed active shade structures in a landscape like arbors and trellises overgrown with live leaf surfaces can dissipate a great amount of heat if water is available. A low density hardscape framework covered with live plant tissue transpires water and dissipates heat. Dissipating heat both disrupts advected heat flow into a landscape and conditions air flow. Evaporative surfaces are critical within (and surrounding) a landscape to manage heat loads on trees.

Heat Dissipating Design!

Building a heat dissipating landscape with trees is challenging. Heat sources and water availability must be identified and used to manage sources of heat generation. Great tree-literate designs and maintenance practices must be installed which deal with heat problems, while monitoring other stress concerns. As in all tree management, a stress / strain like heat load must be recognized and treated. Do not obsess about visual symptoms, but find solutions for the causes of tree stress.

Citation:

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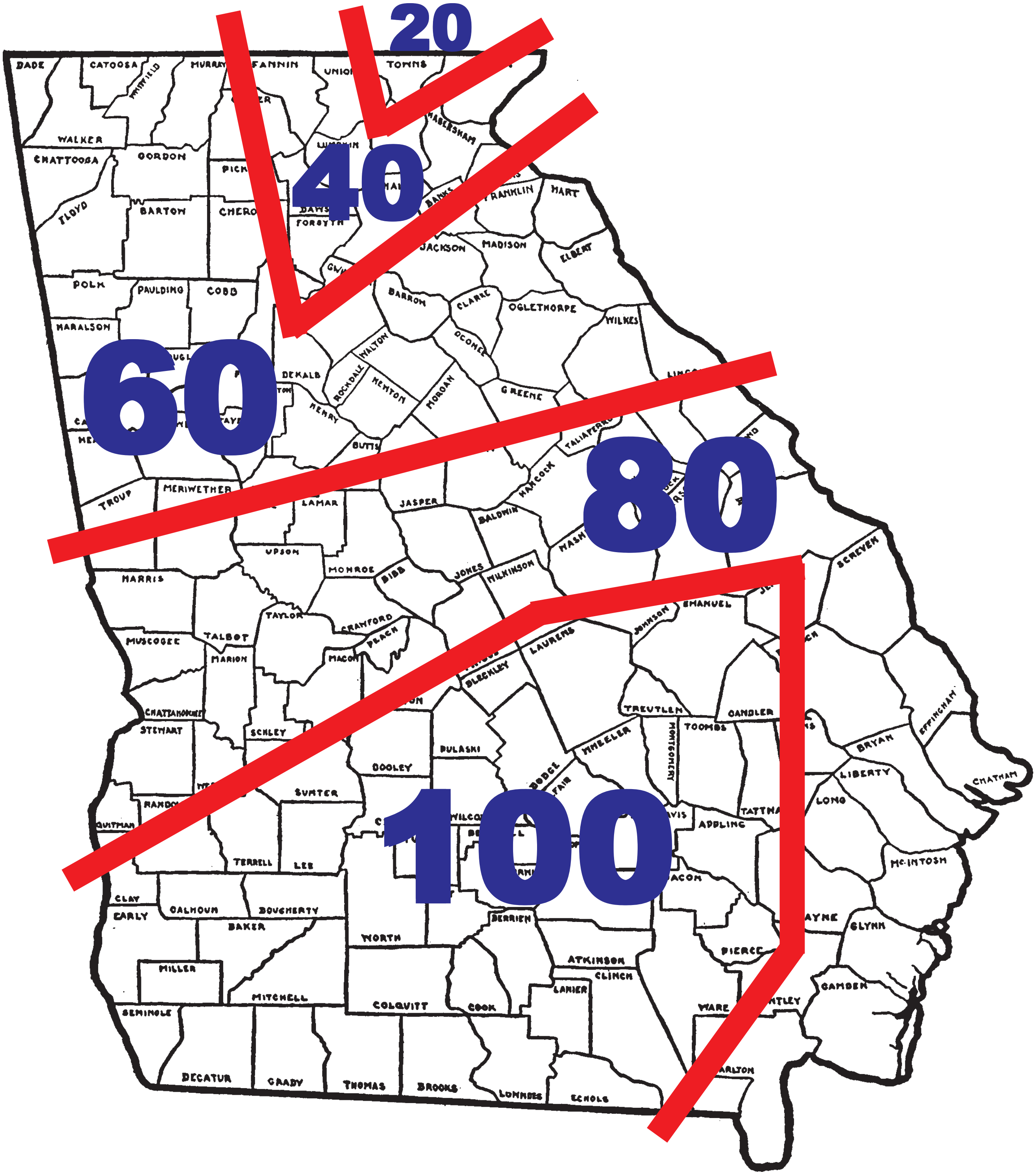

Figure 1: Long-term average number of days above 90^{O}F.
(30 year annual Georgia average, rounded to next highest class.)

relative humidity (%)	air temperature (F°)				
	50°	60°	70°	80°	90°
100	0	0	0	0	0
99	-13	-13	-14	-14	-14
98	-26	-27	-27	-28	-28
95	-67	-68	-70	-71	-72
90	-138	-140	-143	-145	-148
70	-466	-475	-483	-492	-500
50	-905	-922	-939	-956	-971
30	-1,572	-1,602	-1,631	-1,660	-1.687
10	-3,006	-3,064	-3,119	-3,175	-3,226

Figure 2: Estimated water potential (bars) of air for various relative humidity values (percent) and temperatures (F°).

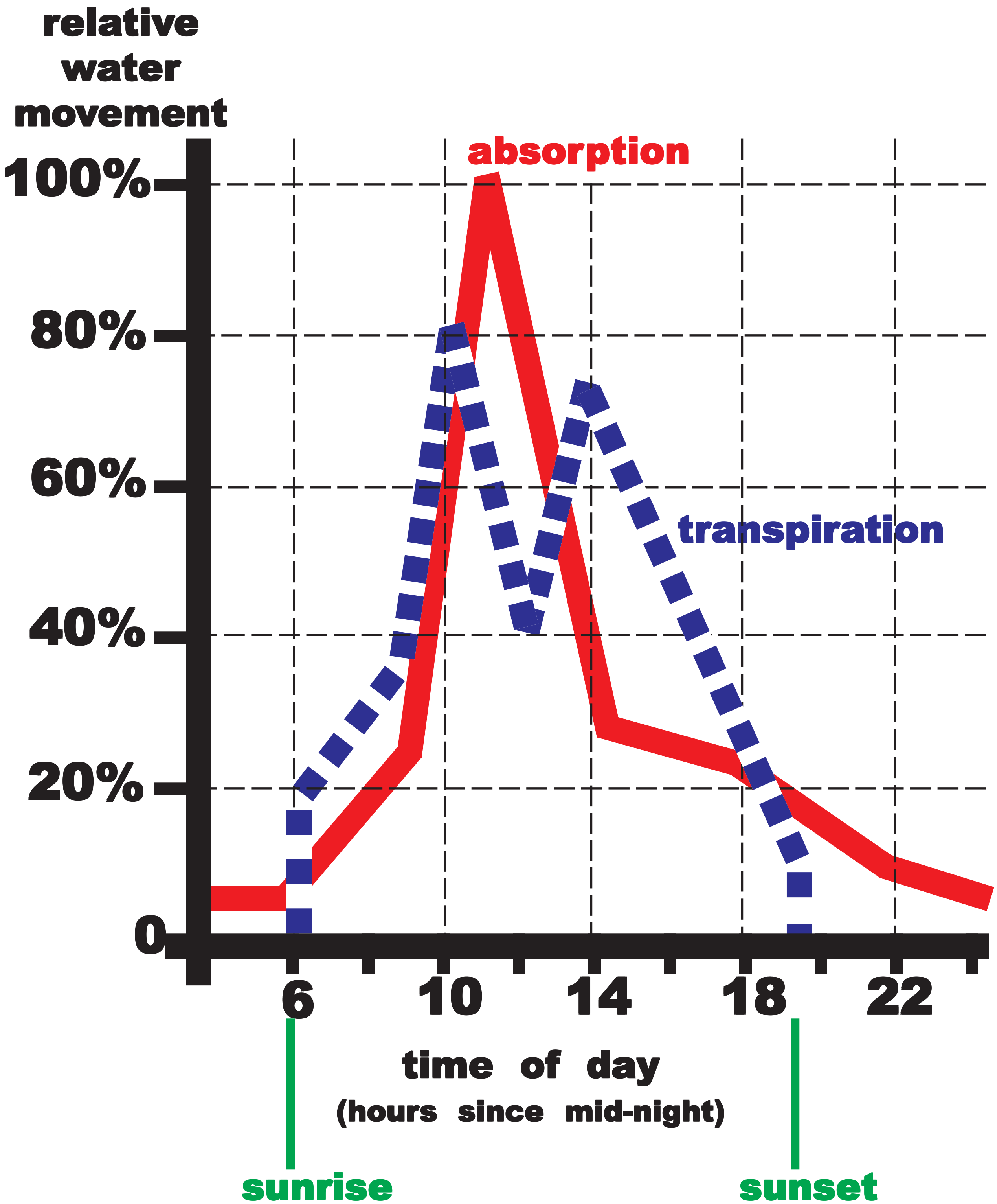

Figure 3: Relative difference between leaf transpiration and root absorption of water in a tree during a warm sunny day with adequate soil moisture.

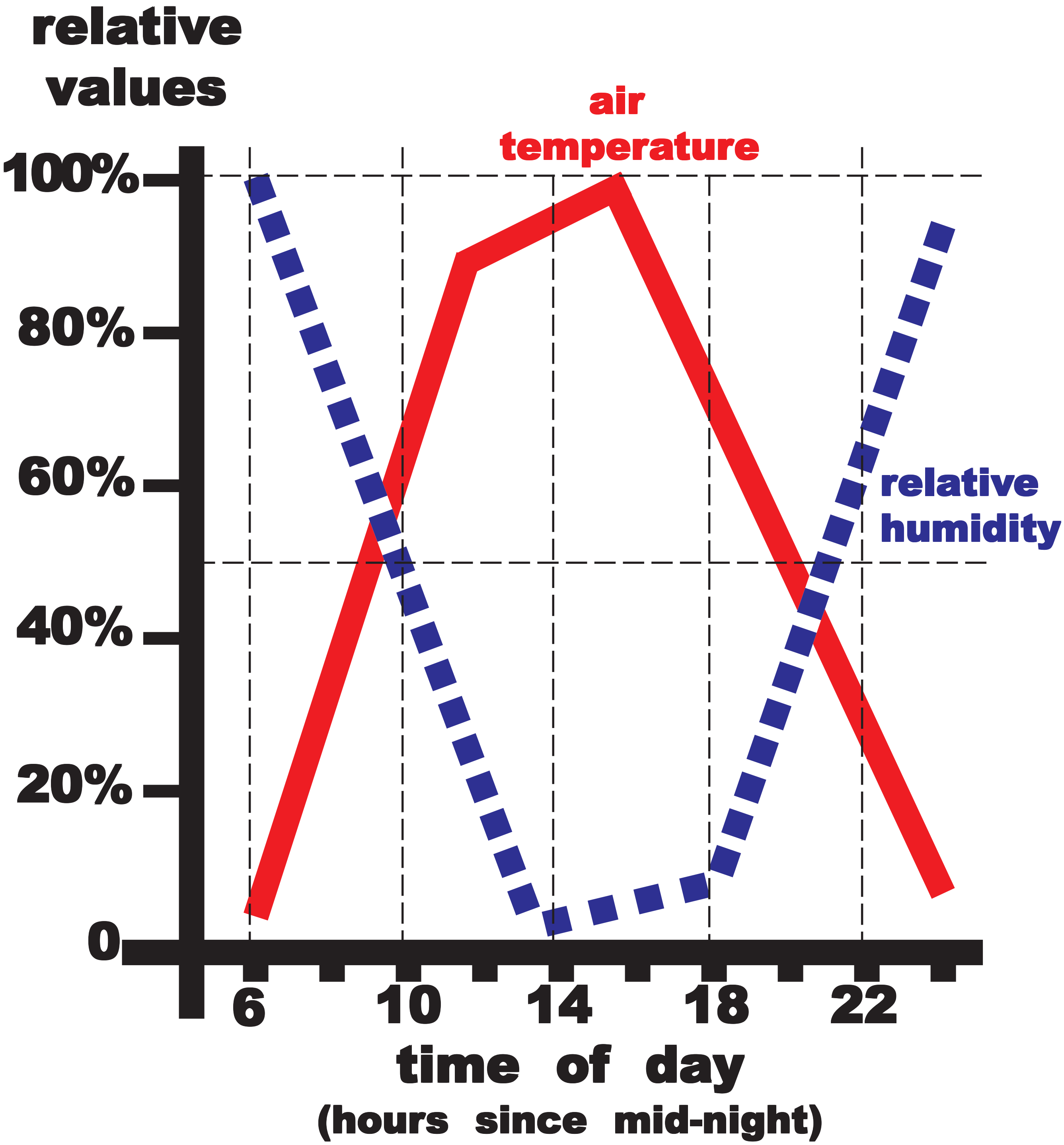

Figure 4: Relative change over a Summer day between air temperature and relative humidity.

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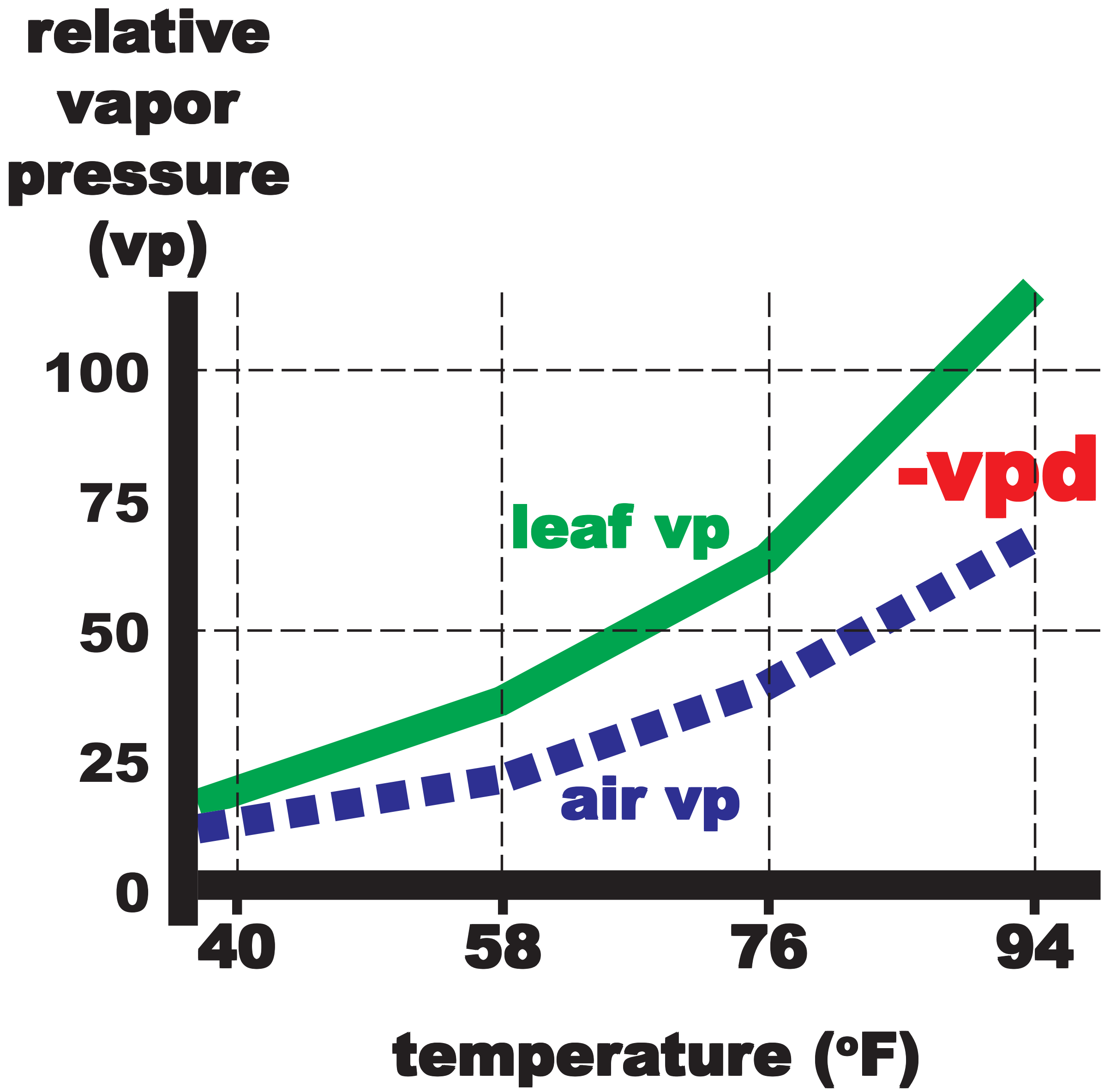

Figure 5: Effects of temperature changes on vapor pressure deficit (- vpd), or dryness of the air.

temperature	multiplier effect
40°F	1X
58°F	2X
76°F	4X
94°F	8X
112°F	16X
130°F	32X

Figure 6: Water-use doubling sequence for trees exposed to increasing heat loads. For each 18°F (10°C) site temperature increase above 40°F, water use by tree and site double from the physical impacts of heat.

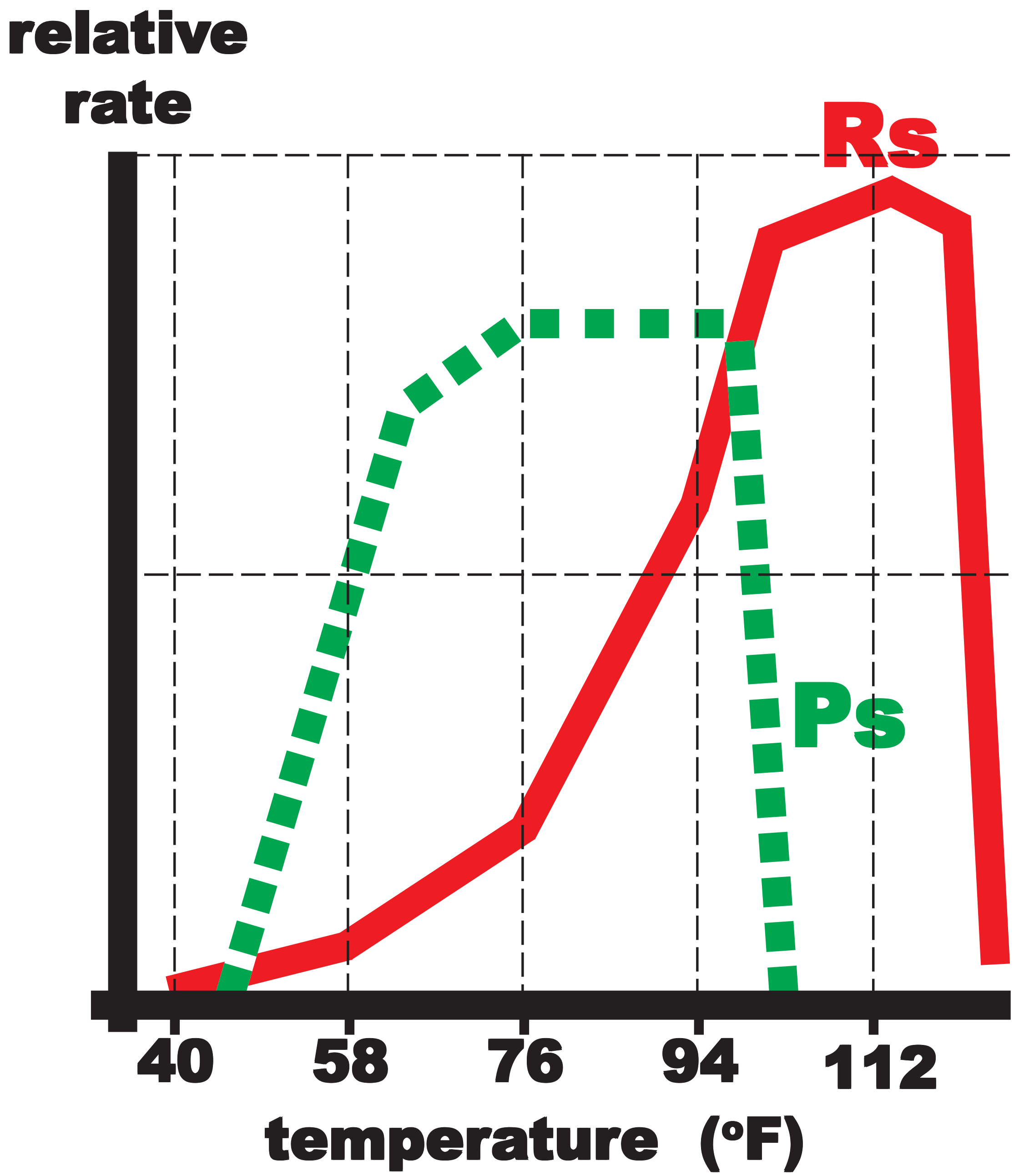

Figure 7: The relative rates of photosynthesis (Ps) and respiration (Rs) in a tree with increasing temperature.

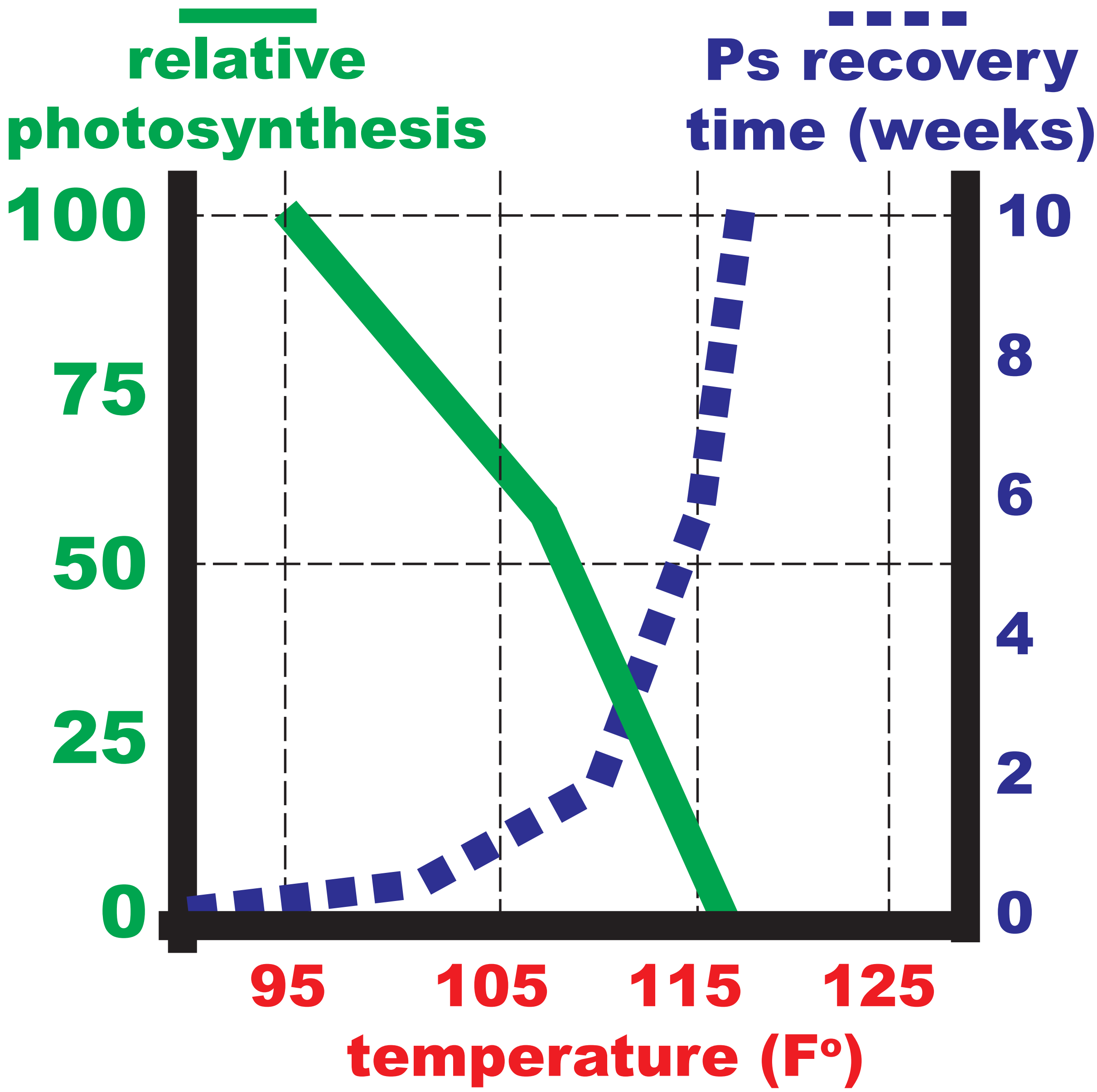

Figure 8: Permanent photosynthesis impact from high temperature exposure (solid line) and associated tree recovery time in weeks (dotted line).